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DRAWINGS ATTACHED

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## (54) METHODS AND APPARATUS FOR PLUGGING WELL BORES WITH HARDENABLE FLUID SUBSTANCES

(71) We, SCHLUMBERGER INLAND SERVICES INC., a Corporation of Panama, 19 Berkeley Street, London, W1, England, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

In various well-completion operations it is often desired to place a fluid-tight barrier or plug at a desired location in a well bore below the lower end of a substantially-smaller well pipe or tubing string. It will, of course, be appreciated that conventional bridge plugs that are small enough to pass through a small-diameter tubing string are incapable of being expanded to a diameter equal to that of the well bore which may be 2 to 5 times greater than the tubing diameter. Accordingly, so-called "through-tubing bridge plugs" such as those shown in U.S. Patent Nos. 3,460,618, 3,460,624 and 3,460,625 are typically employed for situations of this nature.

As illustrated in these patents, these through-tubing bridge plugs generally include a fluid-displacement device that is supported by a suspension cable and releasably coupled to an elongated body member therebelow carrying an expansible tubular bag that is initially retained in a collapsed position. Once the tool has passed through a reduced-diameter tubing string and is in the enlarged well bore below the lower end of the tubing string, a fluent substance such as a hardenable plastic or cementitious composition is selectively discharged from the displacement device into the expansible bag so as to firmly expand the bag into sealing contact with the walls of the well bore therearound. Thereafter, once the hardenable substance within the expanded bag has hardened, the well bore will be tightly plugged so as to prevent fluid or pressure communication between the well bore intervals above and below this barrier.

It will, of course, be appreciated that until the fluent substance has completely hardened, the bag and at least the lower portions of the tool carrying the expanded bag must be secured against movement upwardly or downwardly in the well bore. Accordingly, as described in the aforementioned patents, a fluid bypass passage is provided through each tool for equalizing the pressures above and below the expanded bag as well as for accommodating at least a substantial vertical movement of any flowing well bore fluids during the time that the fluent material is hardening. After the fluent substance has hardened, this bypass passage is permanently closed to complete the formation of the fluid-tight well bore barrier. In some instances, these through-tubing bridge plugs are also provided with selectively-extendible wall-engaging anchors such as those shown in aforementioned U.S. Patent No. 3,460,624 and U.S. Patent No. 3,460,625. In this manner, upon operation of the tool, these wall-engaging anchors will securely anchor the tools against longitudinal movement in the well bore until the fluent substance has fully hardened.

Although these well-completion tools have met with considerable commercial success, the problem of securing the tools while the fluent substance hardens is still not fully solved. For instance, those skilled in the art will appreciate that with those tools having extendible anchors, should it subsequently become necessary to remove the bridge, the typical drilling-out operations will be further complicated by the presence of these anchoring members which are usually formed of iron or steel. Similarly, should some malfunction prevent the expansible bag from fully expanding into sealing engagement with the walls of the well bore, the subsequent removal of the tool will be complicated by the extended anchors. On the other hand, with those tools that do not employ wall-engaging anchors (such as those tools shown in U.S. Patent No. 3,460,618), it will be recognized that it is always possible that the bypass passage through the tool will be too small to accommodate a

substantial movement of fluids in the well bore; and, as a result, the attendant pressure differential will tend to shift the tool before the fluent substance in the expanded bag has fully hardened. Thus, with tools of this nature, it is often preferred to not uncouple the fluid-displacement device from the lower portion of the tool until the fluent substance has hardened. This, of course, will require that the surface equipment be left in position for a considerable time if it is necessary to be certain that the tool is not shifted from its intended location.

Accordingly, it is an object of the present invention to provide new and improved methods and apparatus for securely anchoring an expanded container of a fluent substance in a well bore so as to prevent movement of the container by unbalance well pressures.

This and other objects of the present invention are attained by positioning a yieldable, enclosed container of an initially-fluent hardenable substance at a selected location in a well bore and applying opposed axial forces to the opposite ends of the container while this substance is still fluent for forming the yieldable container into a generally-toroidal configuration. Alternatively, an initially-fluent hardenable substance can be dumped on top of the expanded bag which, in this instance, is filled with a fluent substance that may be either hardenable or non-hardenable. In either case, unbalanced pressure forces acting on the depressed ends of the container will be effective for urging the walls of the container outwardly against the well bore walls with a correspondingly-increased force to frictionally retain the container at its selected location until the hardenable substance has had time to harden into a solidified mass.

According to one embodiment of the invention the container is a tubular bag around a body and at least one end thereof is adapted for longitudinal movement toward the other end of the bag. An axial force is provided against one end of the bag by selectively operable biasing means to move said one end towards the other end and form the expanded bag into a generally-toroidal configuration, so that unbalanced pressure forces acting on the bag will be effective for securely anchoring the apparatus in the well bore as the hardenable fluid substance is hardening into a solidified mass.

The invention, together with further objects and advantages thereof, may be best understood by way of the following description of exemplary apparatus and methods employing the principles of the invention as illustrated in the accompanying drawings, in which:

FIGURE 1 depicts a preferred embodiment well-completion tool arranged in accordance with the principles of the present invention as the tool is being lowered through a tubing string to a desired location in a well bore;

FIGURES 2A—2C are successive cross-sectioned elevational views of the tool depicted in FIGURE 1 illustrating the initial positions of the various elements thereof before the tool has been actuated;

FIGURES 3—6 successively depict the tool shown in FIGURE 1 as it is being operated in accordance with the methods of the present invention; and

FIGURE 7 graphically represents the design criteria of the present invention.

Turning now to FIGURE 1, a well-completion tool 10 incorporating the principles of the present invention and dependently supported by a suspension cable 11 is depicted as it is being lowered through a string of tubing 12 toward a selected position below the lower end of the tubing string within a larger-diameter well bore 13 which, in this instance, is cased as at 14. If desired, a typical casing collar locator 15 may be incorporated with the tool 10 for determining the depth at which the tool is to be halted. In the preferred embodiment depicted, the well-completion tool 10 includes selectively-operable fluid-displacement means 16 arranged in an upper section 17 thereof and carrying a supply of an initially-fluent hardenable material which, upon commond from the surface, is selectively displaced into an expansible tubular bag 18 carried on an elongated body 19 detachably mounted below the housing section. As will subsequently be explained in detail, once the tubular bag 18 has been filled with a sufficient quantity of the fluent substance to expand it outwardly into sealing engagement with the well casing 14, biasing means 20 carried on the body 19 are arranged for selectively imposing opposed axial forces against the ends of the expanded bag to form it into a toroidal shape. The upper section 17 of the tool is then released from the lower body and returned to the surface. Thereafter, once sufficient time has elapsed for the fluent substance to adequately harden so as to form an impermeable transverse barrier or bridge plugging the well casing 14, valve means 21 mounted on the lower end of the body 19 are operatively arranged for closing a bypass passage 22 provided through the body of the tool 10 for reducing or, hopefully, equalizing pressure differentials acting across the inflated bag as the fluent substance therein is hardening.

Turning now to FIGURES 2A—2C, a cross-sectioned elevational view is shown of the well-completion tool 10 as it appears before the collapsed bag 18 carried thereon is expanded. As depicted, the upper section 17 of the tool 10 is operatively arranged for carrying a substantial volume of an initially-fluent, hardenable substance 23 which, upon operation of the selectively-operable fluid-displacement means 16, is forcibly displaced into the tubular bag 18 to expand it outwardly into sealing engagement with the well casing

14. Accordingly, as depicted in FIGURE 2A, the upper housing section 17 of the tool 10 is arranged to provide an enlarged chamber 24 in its upper portion that is joined by an axial passage 25 to an enlarged-diameter longitudinal bore 26 extending substantially the full length of the housing section and terminating at its lower end. The upper portion 27 of the elongated body 19 is also enlarged and similarly provided with an enlarged-diameter longitudinal bore 28 which extends upwardly to the upper end of the body. The opposed ends of the housing 17 and the body 19 are complementally fitted together and fluidly sealed as at 29, with the two members being releasably coupled to one another by latching means 30 to define a combined fluid chamber 31 of substantial length and volumetric capacity.

The fluid-displacement means 16 further include a piston 32 operatively arranged in the fluid chamber 31 so as to be initially positioned just above the upper surface of the initially-fluent substance 23 disposed in the intercommunicated bores 26 and 28 defining the fluid chamber. In this manner, upon downward movement of the piston 32, the fluent substance 23 will be forcibly displaced downwardly from the fluid chamber 31 and into the expansible bag 18 mounted on the body 19 therebelow. It will, of course, be appreciated that by providing lateral ports, as at 33 and 34, in the housing section 17, the well bore fluids will be admitted into the longitudinal housing bore 26 so as to maintain the space above the piston 32 as well as the fluent substance 23 in the fluid chamber 31 at the hydrostatic pressure of the well bore fluids.

In the preferred manner of moving the displacement piston 32 downwardly, the fluid-displacement means 16 further include a cylindrical weight 35 initially disposed in the enlarged bore 26 immediately above the piston and releasably supported therein by means such as two or more upwardly-extending, inwardly-biased latch fingers 36 arranged on an upright rod 37 on the upper end of the weight. As illustrated in FIGURE 2A, the latch fingers 36 have laterally-opposed, outwardly-enlarged heads 38 which are adapted to be received in an enlarged portion 39 of the axial housing passage 25 immediately above the upper end of the enlarged-diameter longitudinal bore 26. In this manner, so long as the latch fingers 36 are laterally separated, their respective enlarged heads 38 are supported on the upwardly-directed shoulder 40 defined at the lower end of the recess 39. To retain the latch fingers 36 initially separated from one another, an actuating piston 41 is disposed in the enlarged chamber 24 and coupled to a depending axial rod 42 which extends through the axial passage 25 into the enlarged recess 39 so as to be interposed between the opposed enlarged heads 38 of the latch fingers 36 so long as the actuating piston is not further elevated by a compression spring 43 mounted within the enlarged chamber.

To retain the actuating piston 41 in its initial position illustrated in FIGURE 2A, the upper portion of the chamber 24 is initially filled by a relatively non-compressible fluid 44 such as water or oil; and this fluid is retained therein so long as a normally-closed solenoid valve 45 connected to suitable electrical conductors 46 and 47 in the cable 11 is not operated to open communication by way of a fluid passage 48 between the enlarged chamber and the exterior of the tool 10. If desired, a separate fluid passage 49 may also be provided for filling the chamber 24, with communication in the reverse direction through the filling passage being prevented by means of a suitable valve such as a ball check valve 50 arranged to prevent flow out of the chamber without unduly limiting the admission of the fluid 44 thereinto. Accordingly, it will be appreciated from FIGURE 2A that once the chamber 24 has been filled with a sufficient volume of the fluid 44 to shift the actuating piston 41 downwardly to its illustrated position, the depending rod 42 thereon will be positioned between the opposed enlarged heads 38 for maintaining the weighted body 35 suspended just above the displacement piston 32.

In the preferred manner of arranging the latching means 30, the lower end of the housing section 17 is adapted to be complementally received within the upper end of the enlarged longitudinal bore 28 in the elongated body 19. An inwardly-opening circumferential groove 51 is formed around the wall of the internal bore 28 and adapted for receiving outwardly-enlarged heads 52 on the lower ends of two or more yieldable latch fingers 53 dependently coupled to the lower end of the upper housing section 17. A ring 54 is normally positioned in the longitudinal bore 28 to the rear of the enlarged heads 52 and suitably dimensioned to retain the enlarged heads within the circumferential groove 51 until the ring is shifted downwardly in relation to the heads. To retain the ring or annular latch member 54 in its depicted elevated position, an upstanding support 55 is coupled thereto and extended upwardly into the lower end of the housing section 17 thereabove. An annular plate 56 is mounted around the upper end of the support 55 and slidably arranged within an inwardly-facing recess 57 within the bore 26 and supported therein by a spring 58 which normally urges the annular plate upwardly against the downwardly-facing surface at the top of the recess.

In this manner, so long as the annular plate 56 is elevated as depicted in FIGURE 2A, the latch ring 54 is engaged with the reverse side of the enlarged heads 52 to reliably retain them within the circumferential housing groove 51 and, accordingly, securely latch the tool

sections 17 and 19 together. It will be appreciated, however, that upon downward travel of the displacement piston 32 through the enlarged housing bore 26, the piston will ultimately contact the annular plate 56 and shift it downwardly a sufficient distance to displace the latch ring 54 below the enlarged heads 52 so as to permit the upper tool section 17 to be uncoupled from the elongated body 19 by simply pulling on the suspension cable 11.

To initially retain the fluent substance 23 within the fluid chamber 31, the lower end of the enlarged longitudinal body bore 28 is normally closed by valve means 59 which, in the preferred embodiment of the tool 10 depicted in the drawings, include an annular valve element 60 that is slidably arranged and fluidly sealed, as at 61, within an enlarged chamber 62 formed in the body 19 immediately below the lower end of the enlarged body bore. To normally secure the valve member 60 in its depicted elevated position, means such as a shear pin 63 are provided for releasably retaining the valve member to the elongated body 19 until the fluid pressure of the fluent substance 23 has been increased sufficiently to break the shear pin and shift the valve member downwardly.

For reasons that will subsequently become apparent, an elongated tubular member 64 is coaxially supported within the elongated body bore 28 and terminated at its upper end by a fitting, such as a tee 65, having one or more lateral outlets 66 to provide communication between the upper end of the tubular member and the exterior of the tool 10. By providing an enlarged-diameter portion 67 on the tubular member 64 immediately adjacent to the normal elevated position of the annular valve member 60 and arranging a sealing member 68 thereon for engagement within the axial bore 69 of the annular valve member, the fluent substance 23 thereabove cannot be displaced from the fluid chamber 31 until the annular valve member has moved downwardly a sufficient distance to bring its upper end below the sealing member 68.

The intermediate tubular portion 70 of the elongated body 19 is sufficiently reduced in diameter to accommodate a pair of longitudinally-spaced collars 71 and 72 which are respectively slidably mounted and fluidly sealed, as at 73 and 74, around the reduced-diameter portion of the body and secured, as by bands 75 and 76, within the opposite ends of the elongated tubular bag 18 which is preferably formed of a suitable wear-resistant, flexible and fluid-impervious material, such as a Dacron (Trade Mark) cloth impregnated with neoprene, that does not readily stretch. The bag 18 is, therefore, formed with an expanded diameter corresponding generally to that of the well casing 14; and, preferably, folded around the intermediate body portion 70 in such a manner as to minimize its lateral dimensions and, if desired, lightly tied in its folded or collapsed position by string or tape. In its initially-collapsed position illustrated in FIGURE 2B, the tubular bag 18 is drawn to its full length with the slidable collars 71 and 72 at their most-widely separated positions along the body portion 70; and the upper collar is releasably secured in its initial position by means such as one or more upright latch fingers 77 which are inwardly biased to retain enlarged heads 78 thereon in a circumferential groove 79 around the body portion 70.

It will be noted that by virtue of the sealing members 73 and 74 on the slidable collars 71 and 72, the interior of the bag 18 defines a fluid-tight space 80 therein around the intermediate body portion 70. Accordingly, to provide communication into the fluid-tight space 80 within the collapsed bag 18, one or more lateral ports 81 are provided in the reduced-diameter body portion 70 at a location between the position of the upper collar 71 as shown in Figure 2B and the position to which the collar will slide relative to the body portion 70 when the body portion is raised after the bag 18 is initially expanded. The lower end of the elongated tubular member 64 is extended below the ports 81 and sealingly engaged, as at 82, within the longitudinal bore 83 through the tubular body portion 70. Thus, so long as the upper collar 71 is retained in its initial elevated position by the latch fingers 77, once the valve member 60 is shifted downwardly, the fluent substance 23 released from the fluid chamber 31 will be directed through the annular space 84 around the lower portion of the tubular member 64 and into the bag 18 by way of the lateral ports 81.

It will, of course, be appreciated that once the upper collar 71 has been carried downwardly (as will subsequently be described) a sufficient distance to position the sealing member 73 on the collar below the lateral ports 81, the fluent substance 23 confined in the interior space 80 within the expanded bag will be trapped therein. For reasons that will subsequently be explained, a second circumferential groove 85 is formed around the reduced-diameter body portion 70 just below the lateral ports 81 so that, once the collar 71 has shifted downwardly in relation to the ports, the enlarged heads 78 on the latch fingers 77 will engage this lower circumferential groove to prevent the upper collar from moving upwardly from its lower position.

As previously mentioned, the normally-open bypass passage 22 is provided for reducing, if not altogether equalizing, pressure differentials existing across the expanded bag 18 as the fluent substance 23 therein is hardening. Accordingly, one or more lateral ports 86 are formed in the tubular tool body 70 well below the initial depicted position of the lower collar 72. In this manner, the bypass passage 22

between the upper and lower ports 66 and 86 is defined by the tubular member 64 and the central portion of the longitudinal body bore 83 below the lower end of the tubular member. To selectively close this bypass passage 22, the valve means 21 include a tubular valve member 87 having longitudinally-spaced sealing members 88 and 89 thereon which is operatively arranged within the longitudinal body bore 83 for movement upwardly from an initial position immediately below the lateral ports 86 to a final elevated position (as defined by a downwardly-facing shoulder 90 in the longitudinal bore) where the valve member is adjacent to the lateral ports with its sealing members respectively spanning the ports and sealingly engaged with the body 70 above and below the ports. Thus, in its initial position, fluid communication is readily provided through the tubular member 64 and the ports 60 and 86 for accommodating at least a substantial proportion of any well bore fluids moving upwardly or downwardly past the well-completion tool 10 during the time that the fluent substance 23 is hardening within the expanded bag 18.

In the preferred manner of selectively closing the valve member 87, the upper end of an elongated tension spring 91 is anchored, as by a transverse rod 92, to the intermediate body portion 80 and the spring extended downwardly therefrom through the longitudinal body bore 83. The spring 91 is terminated by a long straight portion 93 which is passed through the valve member 87 and releasably secured in an initially-stretched condition by means of a hook 94 that is coupled to a wire or cord 95 releasably secured to a geared timer mechanism 96 enclosed in an enlarged fluid-filled chamber 97 in the lower portion 98 of the body 19.

In one manner of arranging the timer mechanism 96, the rotational speed of the uppermost gear 99 therein is regulated by a train of gears that is terminated by either a typical escapement and balance (not shown) or a paddle-like wheel member 100 that is driven by the force of the spring 91 acting through the gear train. Thus, by releasably coupling the cord 95 to the shaft 101 carrying the upper gear 99 of the gear train and winding the wire or cord therearound, the tension force of the spring 91 will be effective for slowly rotating this uppermost gear at a speed which, by virtue of the gear train, is regulated by the faster, but retarded, rotational speed of the rotating paddle member 100 in the fluid-filled chamber 97. Accordingly, once the cord 95 is wound around the shaft 101 and coupled to the hook 94 on the lower end of the spring 91, a preselected time interval will be provided before a transverse member, such as a washer 102, loosely mounted on the straight portion 93 of the spring is moved upwardly to shift the tubular valve member 87 upwardly to close the ports 86. In other words, once the cord 95 is connected, the tension force of the spring 91 will begin slowly unwinding the cord from the shaft 101 so that, once the gear 99 has been rotated a sufficient number of revolutions to unwrap the cord therefrom, the lower end of the cord will be released from the shaft and the spring will then jerk the washer 102 upwardly to carry the valve member 87 into its final port-closing position.

The selectively-operable biasing means 20 are preferably arranged on the elongated body 19 below the lower collar 72. As illustrated in FIGURES 2B and 2C, in the preferred manner of arranging the biasing means 20, an annular member 103 is slidably mounted around the elongated body 70 and adapted to be moved upwardly thereon by a stout compression spring 104 carried on an upwardly-directed body shoulder 105 and engaged with the lower end of the slidable annular member. For reasons that will subsequently be explained, the spring 104 is initially retained in compression by latching means such as one or more ball members 106 that are respectively arranged in lateral recesses 107 spaced around the annular member 103 and sized for partial reception in a circumferential groove 108 formed around the intermediate body portion 70. A sleeve member 109 is coaxially mounted around the annular member 103 and has its lower portion formed with an internal diameter appropriately sized in relation to the diameter of the balls 106 and the depth of the circumferential groove 108 to prevent outward lateral movement of the balls from the groove so long as the ball-retainer sleeve remains in the elevated position illustrated in FIGURE 2B.

To permit outward movement of the balls 106 from the circumferential groove 108, longitudinal grooves or slots 110 are arranged in the upper portion of the ball-retainer sleeve 109. Thus, upon downward movement of the retainer sleeve 109 in relation to the annular member 103 to bring the slots 110 respectively into registration with the several balls 106, the upwardly-directed force of the compression spring 104 will be effective for shifting the annular member 103 upwardly in relation to the longated body 70 once the balls are shifted out of the circumferential groove and into the enlarged space provided by the elongated slots. In this manner, it will be appreciated that once the ball-retainer sleeve 109 is moved downwardly against the restraint of a relatively-weak compression spring 111 mounted within an external protective sleeve 112 coaxially arranged around the annular member 103, the stout compression spring 104 will be freed for shifting the annular member upwardly against the lower slidable collar 72. To provide for the actuation of the ball-retainer sleeve 109, the lower portion of the lower

collar 72 is appropriately sized, as at 113, to engaged an inwardly-turned lip 114 on the upper end of the ball-retainer sleeve for shifting the retainer sleeve downwardly in relation to the annular member 103 and the external sleeve 112 for releasing the balls 106.

Accordingly, to prepare the well-completion tool 10 of the present invention for operation, the control chamber 24 above the weight-releasing piston 41 is filled with a sufficient volume of the hydraulic fluid 44 to shift the piston against the spring 43 to a position where the depending rod 42 extends downwardly into the recess 39. The weighted body 35 is forced upwardly, compressing a coil spring 115 thereabove until the enlarged heads 38 of the latch fingers 36 are within the recess 39 on opposite sides of the lower end of the rod 42 and are supported on the shoulder 40 for retaining the weighted body 35 in its elevated position above the fluid-displacement piston 32. The lower end of the upper housing 17 is complementally fitted into the upper end of the upper portion 27 of the elongated body 19 and the latch ring 54 is properly positioned to retain the enlarged heads 52 in the internal circumferential groove 51. The annular valve member 60 is secured in its upper or closed position by the shear pin 63, and the enclosed fluid chamber 31 is then filled with a suitable plastic or cementitious initially-fluent substance which will harden into a solid mass that preferably expands slightly as it fully hardens.

The annular member 103 is shifted into position on the intermediate body portion 70 so as to position the balls 106 in the groove 108 and releasably retain the compression spring 104 in a compressed condition. The tension spring 91 is extended and the hook 94 thereon is connected to the release cord 95 which has been wrapped several turns around the shaft 101 of the upper gear 99 of the timer mechanism 96. As previously mentioned, the predetermined delay before the bypass passage 22 is closed is determined by the number of turns or wraps of the cord 95 around the shaft 101. This time interval is, of course, selected so that the valve member 87 will not be actuated until some time later which is calculated to be sufficient to permit the initially-fluent substance 23 to have at least substantially hardened.

The tool 10 is then lowered downwardly into the well bore 13 by means of the suspension cable 11. Once the well-completion tool 10 has emerged from the lower end of the tubing string 12 and has reached a selected position therebelow, an electrical signal is sent through the cable conductors 46 and 47 to actuate the solenoid volve 45. As previously explained, once the solenoid valve 45 is opened, the hydraulic fluid 44 within the upper chamber 24 will be displaced therefrom by way of the now-opened passage 48 as the compression spring 43 forcibly shifts the weight-releasing piston 41 upwardly. It will be appreciated, of course, that by providing a lateral port 116 in the lower portion of the chamber 24, the weight-releasing piston 41 will be moved upwardly without restraint from any unbalanced pressure forces that would otherwise occur upon opening of the solenoid valve 45 to open the enclosed chamber 24 to the well bore fluids. Once the weight-releasing piston 41 has reached a sufficiently elevated position to withdraw the depending rod 42 from between the opposed ends 38 of the latch fingers 36, the weighted body 35 will be released.

Once the body 35 is released, the force of the compressed spring 115 is effective for accelerating the weighted body downwardly so that it strikes the fluid-displacement piston 32 with considerable impact. In this manner, a substantial shock or pressure wave is developed in the fluent substance 33 which is effective for shifting the annular valve member 60 downwardly with sufficient force to break the shear pin 63. Once the shear pin 63 has failed, the valve member 60 will be moved downwardly a sufficient distance to bring the upper end of the valve member below the seal 68 on the enlarged-diameter portion 67 on the axial tubular member 64 to open communication between the fluid chamber 31 and the filling ports 81 by way of the annular space 84 between the axial tubular member and the inner wall of the intermediate portion 70 of the elongated body 19. A sealing member 117 is arranged on the lower end of the valve member 60 for sealing engagement with the lower portion 118 of the enlarged chamber 62 and prevent loss of the fluent substance 23 through a pressure-equalizing port 119 provided into the chamber below the upper sealing member 61.

Once the weighted body 35 has come to rest on top of the fluid-displacement piston 32, the weight of the body will be effective for moving the piston on downwardly through the fluid chamber 31 to forcibly displace the fluent substance 23 therefrom through the filling ports 81 and into the interior space 80 within the expansible bag 18. It will, of course, be appreciated that since the fluent substance 23 is initially at the hydrostatic pressure of the well bore fluids, the pressure developed by the weighted body 35 will be in addition to the hydrostatic pressure. Thus, as the bag 18 is filling, the increased fluid pressure developed in the fluent substance 23 by the weighted body 35 acting on the displacement piston 32 will be effective for expanding the bag outwardly and into contact with the walls of the well casing 14 immediately adjacent thereto. Expansion of the tubular bag 18 will, of course, be effective for drawing the unrestrained lower slidable collar 72 upwardly along the intermediate body portion 70 toward the still-

latched upper collar 71. It should be noted that the latch fingers 77 are biased inwardly with sufficient force that the expansion of the bag 18 will draw the lower collar 72 upwardly without releasing the enlarged heads 78 from the upper circumferential groove 79.

Accordingly, when the expansible bag 18 is fully expanded, it will assume a position such as depicted in FIGURE 3 in which its opposite ends substantially assume a generally-hemispherical configuration. At this point, there will still be a substantial volume of the still-fluent substance 23 remaining in the fluid chamber 31 so that the increased fluid pressure developed in the interior space 80 by the weight of the body 35 acting on the piston 32 will expand the bag 18 outwardly against the well casing 14 with a moderate lateral force. It will be recognized, of course, that once the bag 18 is fully expanded, the discharge flow of the fluent substance 23 from the fluid chamber 31 will temporarily cease and the displacement piston 32 and weighted body 35 will come to rest at the upper fluid level of the fluent substance in the fluid chamber.

It will be recognized that the fluid pressure expanding the bag 18 outwardly will urge the exterior the bag against the well casing 14 with a lateral force that is effective to frictionally secure the bag against longitudinal movement. Therefore, as illustrated in FIGURE 4, upon upward movement of the suspension cable 11, the upper housing section 17 and the elongated body 19 will be moved upwardly in relation to the stationary expansible bag 18 and the upper and lower slidable collars 71 and 72. As will subsequently be explained in detail, this upward movement is effective for consecutively blocking further communication to the interior space 80 in this expanded bag 18, actuating the biasing means 20, and ultimately freeing the housing section 17 from the elongated body 19.

First of all, upon upward movement of the elongated body 19, the inwardly-enlarged ends 78 of the latch fingers 77 will be cammed outwardly by the lower surface of the upper circumferential groove 79 to release the upper collar 71 from the intermediate body portion 70. Thus, as depicted in FIGURE 4, the continued upward travel of the elongated body 19 will be effective for moving the fill ports 81 above the upper collar 71 and then bringing the lower circumferential groove 85 immediately below the fill ports up to or, perhaps, slightly above the latch fingers 77. It will, of course, be recognized that once the lateral ports 81 pass above the fluid seal 73 on the upper collar 71, the fluent substance within the expanded bag 18 will be sealingly enclosed therein. Moreover, once the lower circumferential groove 85 engages or passes above the latch fingers 77, the upper collar 71 cannot return upwardly in relation to the body to a position where the ports 81 are again in communication with the interior space 80 within the bag 18.

Furthermore, as the elongated body 19 is moved upwardly, the annular member 103 releasably coupled thereto will be carried upwardly toward the stationary lower collar 72 so as to bring the depending portion 113 thereof into contact with the inwardly-directed lip 114 of the ball-retainer sleeve 109. Then, as the elongated body 19 is moved further upwardly, the ball-retainer sleeve 109 will be halted and tre continued movement of the annular member 103 will carry the balls 106 upwardly into registration with the elongated slots 110. As previously described, once the balls 106 move into registration with the elongated slots 110, they will be free to move outwardly into the enlarged space therearound to disengage the balls from the circumferential groove 108 around the intermediate body portion 70.

Accordingly, once the balls 106 are disengaged from the circumferential groove 108, the compressed biasing spring 104 will be released for forcibly urging the annular member 103 upwardly against the lower collar 72. Thus, as best seen in FIGURE 5, once the compression spring 104 is released, it will impose a substantial upwardly-directed axial force against the lower end of the stationary expanded bag 18. This axial force will be effective for further increasing the fluid pressure of the still-fluent substance trapped within the bag 18 which (if the enlarged heads 78 are below the groove 85) will initially move the upper collar 71 upwardly to accommodate the corresponding inward or upward depression of the lower end of the bag. Once, however, the upper collar 71 reaches a position on the intermediate body portion 70 where the latch fingers 77 are adjacent to the circumferential groove 85 just below the filling ports 81, the enlarged ends 78 thereof will be urged into the circumferential groove 85 to secure the upper collar from further upward movement. Once the upper collar 71 is secured against further movement in relation to the elongated body 19, the upwardly-directed axial force imposed on the lower end of the bag 18 by the stout compression spring 104 will be effective for developing a downwardly-directed opposing or axial reaction force on the upper end of the bag for depressing the central portions of the upper and lower ends of the bag inwardly so that, ultimately, the bag will assume the generally-toroidal configuration depicted in FIGURE 5.

It will be appreciated, therefore, that once the well-completion tool 10 has reached the particular stage of its operation depicted in FIGURE 5, the fluent substance trapped within the interior space 80 of the expanded bag 18 will be at a fluid pressure which is equal to the sum of the hydrostatic pressure

of the fluids in the well bore 13, the increased pressure developed by the displacement piston 32 during the filling of the bag and the further-increased pressure developed therein by the opposing axial forces imposed thereon by the released compression spring 104. The perimeter of the bag 18 will, therefore, be urged outwardly against the wall of the casing 14 with a total force that is proportionally related to the total pressure of the still-fluent substance confined within the expanded bag. Accordingly, once the bag 18 is securely anchored in this manner, the upper housing portion 17 of the tool 10 is separated from the elongated body 19 by simply pulling further on the suspension cable 11 so that the latch fingers 53 will be released from the circumferential groove 51 at the upper end of the elongated body once the displacement piston 32 has engaged the annular plate 56 and shifted the ring 54 below the heads 52.

It will be appreciated from FIGURES 4—6 that, once the filling ports 81 are uncovered, the weighted body 35 will continue moving the piston 32 downwardly to displace the remainder of the fluent substance 23 contained within the fluid chamber 31 into the well bore annulus defined between the casing 14 and that portion of the elongated body 19 projecting upwardly above the expanded bag 18. In this manner, an additional quantity of the fluent substance 23 will be deposited on top of the expanded bag 18 to further assure that an impermeable plug or barrier will be formed in the well bore 13 once the fluent substance has ultimately expanded and hardened. In any event, by virtue of the increased anchoring force provided by the toroidal shape of the bag 18, the upper section 17 of the tool 10 can be released from the elongated body 19 and returned to the surface without having to wait for the fluent substance to harden. Then, as shown in FIGURE 6, at some predetermined time thereafter, the timer mechanism 96 will function to release the tension spring 91 so as to shift the annular valve member 87 upwardly across the lower bypass ports 86 and permanently close the bypass passage 22.

It will, of course, be recognized that so long as the fluent substance confined in the expanded bag 18 has not yet hardened, once the upper section 17 of the tool 10 is released from the elongated body 19 the only force retaining the bag and body in position in the well bore 13 will be the frictional force between the bag and the well casing 14. This frictional force is, therefore, determined by:

$$F_h = P_b\ (\pi DL)\,\mu \qquad \text{(Eq. 1)}$$

where,

$F_h$=frictional force holding bag stationary in relation to well casing;

$P_b$=internal pressure of fluent substance in expanded bag;

D=diameter of expanded bag;

L=length of expanded bag in contact with well casing; and

$\mu$=coefficient of static friction between expanded bag and well casing.

Accordingly, so long as those forces tending to move the expanded bag 18 in the well bore 13 do not exceed the above-defined frictional force ($F_h$) the expanded bag and elongated body 19 will remain stationary in the well bore. It will be appreciated that the major force tending to move the expanded bag 18 and the body 19 will be the total force acting on the cross-sectional area of the bag as a result of any pressure differential between well bore fluids above and below the bag. Thus, an unbalanced pressure force tending to displace the bag 18 and body 19 will be equal to:

$$F_p = \Delta P\left(\frac{\pi D^2}{4}\right) \qquad \text{(Eq. 2)}$$

where,

$F_p$=force tending to displace bag as a result of pressure differential acting in either direction across expanded bag;

$\Delta P$=pressure differential acting across expanded bag; and

D=diameter of the expanded bag.

It will be appreciated, therefore, that by setting ($F_h$) in Equation 1 equal to ($F_p$) in Equation 2 and combining the two equations, the resulting equation will define the pressure differential required to shift the frictionally-anchored expanded bag 18 and the body 19. Thus,

$$\Delta P\left(\frac{\pi D^2}{4}\right) = P_b\ (\pi DL)\,\mu;$$

and

$$\Delta P = \frac{4\,\mu\,L}{D}\,P_b. \qquad \text{(Eq. 3)}$$

Plotting $\Delta P$ against $P_b$, as obtained from Equations 3 for a given size of the expanded bag 18, a straight line, as at 120 in FIGURE 7, is obtained. Thus, as represented there, it will be appreciated that so long as the point of intersection of ($\Delta P$) and ($P_b$) for a given situation is below or to the right of the plotted line 120, the expanded bag 18 and body 19 will remain stationary in the well bore 13. On the other hand, should the pressure differential ($\Delta P$) increase to a level where its point of intersection with the particular bag pressure ($P_b$) is above or to the left of the plotted line

120, the bag 18 and elongated body 19 will move in the well bore 13.

Accordingly, in the present invention, it has been found that an initial holding force ($F_h$) of increased magnitude can be developed by imposing the axially-directed force of the biasing spring 104 on one end of the expanded bag 18 and securing the other end of the bag against movement in relation to the body 19 so as to provide the opposing axially-directed reaction force on that end of the bag and thereby reform the bag into the generally-toroidal configuration depicted in FIGURES 5 and 6. It will be appreciated, therefore, that upon the upward movement of the lower collar 72 by the spring 104 toward the upper collar 71, the internal volume of the space 80 within the expanded bag 18 will be slightly reduced as the opposite hemispherical ends of the bag are reformed into their respective inverted or hemitoroidal shapes depicted in FIGURES 5 and 6. Thus, inasmuch as the fluent substance is substantially incompressible, the opposing axial forces imposed on the expanded bag 18 by the spring 104 and upper collar 71 will develop an increased internal pressure within the bag for producing a correspondingly-greater initial frictional holding force ($F_h$). Moreover, of paramount significance, it has been found that once the bag 18 assumes the generally-toroidal configuration, increasing pressure differentials acting on the bag will further increase the holding force ($F_h$) at a faster rate than the rate of increase of the pressure force ($F_p$) tending to shift the tool 10.

To demonstrate the new and improved operation of the biasing means 20, a tubular bag 18 of a selected length and diameter that is appropriate for typical well-completion operations was mounted on the elongated body 19. The bag 18 was disposed inside of a section of well casing and inflated to a moderate pressure by filling the bag with a typical fluent, cementitious substance. Once the bag 18 was filled, a pressure differential was imposed across the bag and progressively increased until longitudinal movement of the bag and body was noted. The results of this test are illustrated by the curve 121 in FIGURE 7, with slippage of the bag 18 occurring at the upper end of this curve. It should be noted that during this test the ends of the bag 18 remained generally hemispherical since there were no concentrated axial forces being applied to the bag.

The same test was repeated by inflating the bag to the same initial pressure but with successively-increasing, concentrated spring forces now being applied axially against one end of the expanded bag 18 while the slidable collar 71 at the other end of the bag was secured to the body 19. Using the data obtained from these tests, representative curves such as those depicted at 122—124 in FIGURE 7 were plotted to portray the new and improved effects of the axially-directed, opposed forces ($F_1$, $F_2$ and $F_3$) provided by the spring 104 and the secured collar 71 arranged in accordance with the principles of the present invention. As a result, it was discovered that, once the spring 104 was released and the ends of the bag 18 depressed into their hemitoroidal configuration, increases in the pressure differential across the expanded bag progressively increased the holding force ($F_h$) at a much-faster rate than the holding force obtained where the bag had hemispherical ends (curve 121). Thus, as illustrated by the curves 122—124, the resulting increased holding forces provided by the axial biasing spring 104 tend to asymptotically approach the limiting line 120 and thereby within the limits of the bursting strength (line 125) provides a safe margin between the resulting holding force and the point where slippage will occur. Moreover, as shown by the curves in FIGURE 7, a stouter spring (e.g., curve 124) will develop a correspondingly stronger holding force than a lighter spring (e.g., curve 122) at the same pressure differential ($\Delta P$).

It will, therefore, be appreciated that the most effective operation of the tool 10 is achieved by selecting a spring rate for the biasing spring 104 that will result in the internal pressure of the expanded bag 18 approaching the rated bursting pressure of the bag at about the point that the pressure differential across the bag is about to cause the tool to slip in relation to the casing 14. In other words, if the spring 104 is too weak (as depicted by the curve 122), the tool 10 will shift at a relatively-low pressure differential; and if the biasing spring is too stout, the bag 18 will burst at a low pressure differential. The selection of the spring 104 will, of course, be dependant upon such factors as the expanded diameter of the bag 18, the bag material, the internal bag pressure before the biasing spring is released, etc. In any event, routine tests such as those described above will readily establish the optimum selection for the spring 104 for any given design of the tool 10. Thus, as far as the present invention requires, it is necessary only for the opposed axial forces acting on the opposite ends of the expanded bag 18 to form the bag into a generally-toroidal configuration. The degree or extent of depression of the opposite ends of the expanded bag 18 will govern the rate at which the resulting holding force will increase in response to an increase in the pressure differential acting across the bag.

Accordingly, it will be appreciated that the present invention has provided new and improved methods and apparatus for plugging a well bore with a fluent hardenable substance. By disposing this substance into an enclosed yieldable container that is expanded into contact with the walls of a well bore and impos-

ing an axial force thereon, upon increased pressure differentials acting across the container the container will be secured to the well bore walls with a force that increases at a rate sufficient to maintain the container safely anchored against movement. With apparatus arranged in accordance with the principles of the present invention, a tubular bag is sealingly mounted around an elongated body and has one end thereof adapted for longitudinal movement along the body toward the other fixed end of the bag. Selectively operable means, such as a spring or the like, are operatively arranged on the elongated body for imposing opposing axial forces on the opposite ends of the bag to reform the bag into a generally-toroidal shape once the bag has been filled with a fluent hardenable substance to expand it into sealing engagement with the walls of the well bore. In this manner, the bag and body will be secured in position within a well bore as the fluent substance hardens and will not be shifted by pressure differentials acting thereon. Moreover, should the pressure differential increase sufficiently to burst the bag before this substance hardens, a tool arranged in accordance with the present invention will merely fall into the well bore and can be easily retrieved without having to drill it out as would be the case if mechanical anchors were used.

While a particular embodiment of the present invention has been shown and described, it is apparent that changes and modifications may be made without departing from the scope of the appended claims.

WHAT WE CLAIM IS:—

1. Apparatus adapted for plugging a well bore and comprising: an elongated body adapted to be suspended in a well bore; a tubular bag of a flexible material arranged around said body; first and second coupling means respectively secured to the opposite ends of said bag and operatively sealed around said body for defining an enclosed space therearound within said bag, said first coupling means being adapted for longitudinal movement along said body toward said second coupling means; and first means on said body including a passage communicating with said enclosed space and adapted for admitting a fluent substance into said enclosed space to expand said bag outwardly into contact with a well bore wall; characterized in that said apparatus further includes second means including biasing means arranged on said body and operable after expansion of said bag for moving said first coupling means along said body toward said second coupling means to depress said bag ends axially inwardly and form said expanded bag into a generally-toroidal configuration for anchoring said apparatus in a well bore against movement by unbalanced pressure forces acting thereon.

2. The apparatus of Claim 1 characterized in that said biasing means are selectively operable for forcibly urging said first coupling means toward said second coupling means after said bag is expanded.

3. The apparatus of Claim 2 characterized in that said second means further include means normally disabling said biasing means and selectively operable to engage said biasing means with said first coupling means for urging said bag ends inwardly only after said bag has been expanded outwardly into contact with a well bore wall.

4. The apparatus of Claim 1 characterized in that said second means include spring means operatively arranged on said body for urging said first coupling means closer to said second coupling means with an axial force sufficient to reform said bag into said generally-toroidal configuration, means releasably securing said spring means to said body for retaining said spring means from engagement with said first coupling means, and means selectively operable from the surface for releasing said spring-retaining means to bring said spring means into engagement with said first coupling means.

5. The apparatus of any of Claims 1 to 4 characterized in that said first means further include means operable upon the expansion of said bag into contact with a well bore wall for terminating further communication between said passage and said enclosed space to confine a fluent substance therein once said bag is fully expanded.

6. The apparatus of Claim 5 characterized in that said means operable upon the expansion of said bag into contact with a well bore are responsive to upward movement of said body.

7. The apparatus of any of Claims 1 to 6 characterized in that said first means comprise selectively-operable fluid-displacement means coupled to said body and adapted to fill said enclosed space with an initially-fluent hardenable substance for expanding said bag outwardly into firm frictional contact with a well bore wall and moving said first and second coupling means relatively toward one another to respectively form said bag ends into a generally-hemispherical configuration.

8. The apparatus of any of Claims 1 to 7 characterized in that said second coupling means are adapted for relative longitudinal movement with respect to said body from a first position to a second position closer to said first coupling means after expansion of said bag, and there is provided first latch means adapted for releasably securing said second coupling means in said second position so that upon movement of said first coupling means by said second means toward said second coupling means said bag ends will be depressed axially inwardly toward one another.

9. The apparatus of Claim 8 characterized

in that said first means further include valve means operable upon movement of said second coupling means for terminating further communication between said passage and said enclosed space to confine a fluent substance therein once said bag is fully expanded.

10. The apparatus of Claims 8 or 9 characterized in that said second means are operative for urging said bag ends inwardly only after said second coupling means are releasably secured in said second position and said bag has been expanded outwardly into contact with a well bore wall.

11. The apparatus of claim 1 characterized in that said second coupling means include first latch means operatively arranged between said second coupling means and said body for securing said second coupling means against upward movement relative to said body once said bag is expanded, and said second means include biasing means operatively arranged between said first coupling means and said body for urging said first coupling means toward said second coupling means, and second latch means normally securing said biasing means and responsive to upward movement of said body in relation to said expanded bag and said second and first coupling means to free said biasing means for urging said second coupling means toward said first coupling means once it is secured by said first latch means.

12. The apparatus of Claim 11 characterized in that said biasing means include a compression spring around said body and having its lower end engaged therewith; and said second latch means include a slidable member mounted on said body and engaged with the upper end of said compression spring, a latch member operatively arranged between said slidable member and said body for movement from a first position securing said spring in compression and a second position releasing said spring for upward expansion, a retaining member normally retaining said latch member in its said first position and adapted to be moved away from said latch member upon engagement of said retaining member with said second coupling means upon said further movement of said body for freeing said latch member for movement to its said second position.

13. The apparatus of any of Claims 1 to 12 characterized in that it includes a fluid bypass on said body adapted for providing fluid communication above and below said bag once it expands, and means on said body adapted for closing said fluid bypass after a time sufficient for the fluent substance contained in said bag to solidify into a hardened mass.

14. The apparatus of any one of Claims 1 to 13 wherein said body comprises an upper body and a lower body tandemly coupled to one another and adapted to be supported in a well bore from a suspension cable and said first and second coupling means are fluidly sealed around said lower body and adapted for sliding movement relative to said lower body between longitudinally-spaced positions characterized in that said second means are operatively arranged on said lower body and responsive only to upward movement of said upper and lower bodies for moving said second and first coupling means relatively closer to one another, and that there is provided third means for uncoupling said upper body from said lower body.

15. A method for plugging a well bore wherein an enclosed yieldable container for a fluent substance is positioned in a well bore at a selected location and then expanded to bring the perimeter of said expanded container into engagement with the walls of the well bore to anchor said container in the well bore and a fluent hardenable substance is supported by the expanded container until said fluent hardenable substance has solidified into a hardened mass, characterized in that oppositely directed axial forces are applied on the opposite ends of said expanded container to depress its said ends relatively inwardly and form said container into a generally toroidal configuration for anchoring said expanded container in the well bore while said fluent hardenable substance is solidifying into a hardened mass.

16. A method as claimed in Claim 15 characterized in that said fluent substance in said expanded container is a fluent hardenable substance which is supported by said expanded container until said fluent hardenable substance has solidified into a hardened mass.

17. A method as claimed in Claims 15 or 16 characterized in that a fluent hardenable substance is discharged into said well bore above said expanded container to form a bridge of said hardenable substance on top of said expanded container which will be supported thereby until said fluent hardenable substance has solidified into a hardened mass and plugged the well bore.

18. A method of plugging a well bore substantially as hereinbefore described with reference to and as illustrated in the accompanying drawings.

19. Apparatus for plugging a well bore substantially as hereinbefore described with reference to and as illustrated in the accompanying drawings.

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Agent for the Applicants.

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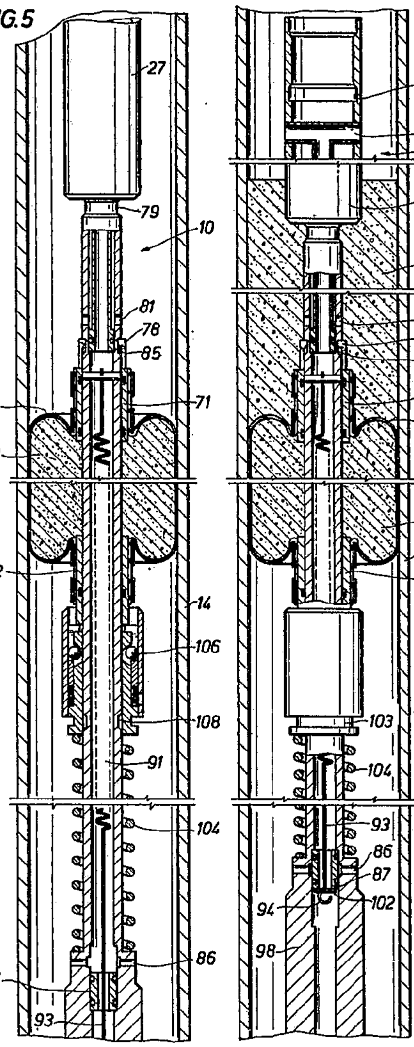
1331797 COMPLETE SPECIFICATION

3 SHEETS *This drawing is a reproduction of the Original on a reduced scale*

Sheet 1

FIG.5

FIG.6



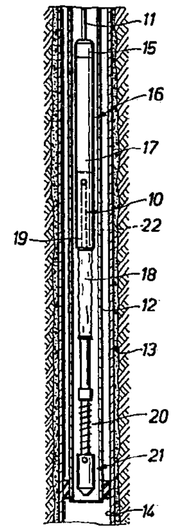




FIG.1

FIG.7

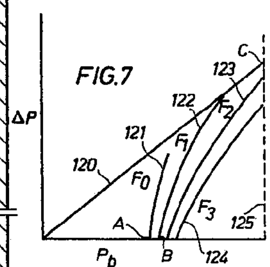


FIG. 2A

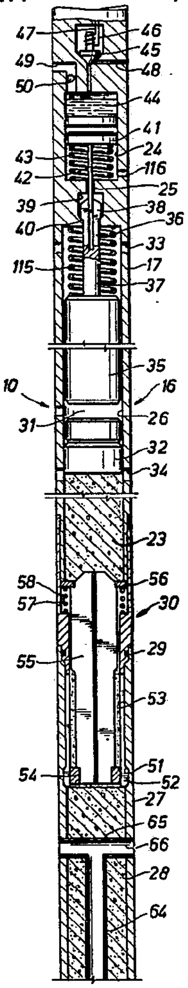



FIG. 2B

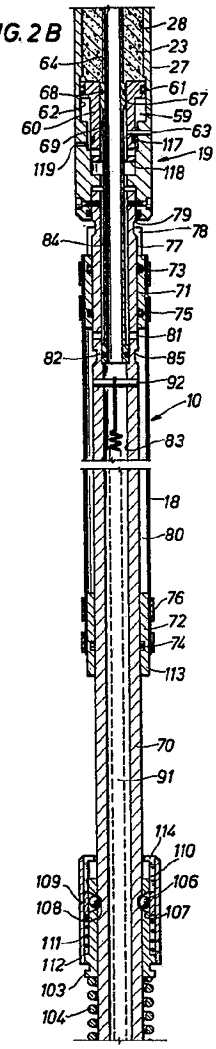



FIG. 2C

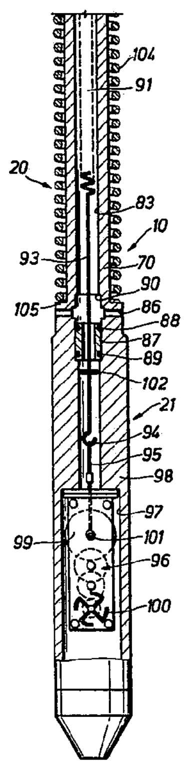


FIG. 3

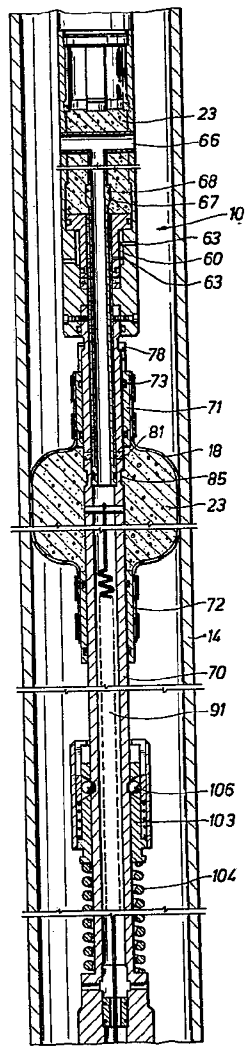

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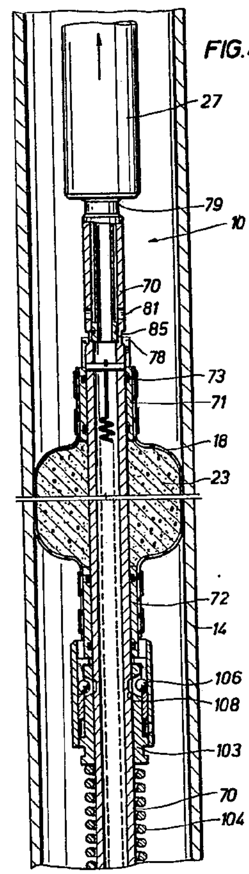
FIG. 4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